Two particle hadron correlations with higher harmonic reaction plane in Au+Au 200 GeV collisions at RHIC-PHENIX

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Outline

- Introduction
  - Higher harmonic plane and flow
  - Ridge and Shoulder
  - Previous 2 particle correlation results
- Motivation
- Data set and measured values
- Results
  - $v_2$, $v_3$, and $v_4$ subtracted correlations
  - $\eta_{\text{trig}}$ dependent $\Delta\eta$ correlations
Higher harmonic plane & flow

- Fluctuations of initial collision geometry lead to higher harmonic deformation
- Deformation is transferred to momentum space by collective expansion (hydrodynamics)
  - higher harmonic anisotropy emerged

Azimuth. distribution
\[
\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi_2) + 2v_3 \cos 3(\phi - \Phi_3) + 2v_4[\Phi_4] \cos 4(\phi - \Phi_4)
\]

Correlation among \(\Phi_2 - \Phi_3 - \Phi_4\)
\[
\langle \cos 6(\Phi_3 - \Phi_2) \rangle = 0 \quad \langle \cos 4(\Phi_4 - \Phi_2) \rangle = \frac{v_4(\Phi_2)}{v_4(\Phi_4)}
\]
$v_3$ : possible source of “Ridge” and “Shoulder”

$$Jet(\Delta \phi) = C_2(\Delta \phi) - b_0 \text{Flow}(\Delta \phi)$$

Ridge : near side long range $\Delta \eta$ correlations

Shoulder: double hump at away side of $\Delta \phi$ correlations (also long in $\Delta \eta$)

- Flow correlation from $v_3$ term $\sim b_0 2v_3^{\text{trig}}v_3^{\text{asso}} \cos 3\Delta \phi$
  - $v_3$ subtraction would reduce Ridge and Shoulder $\Rightarrow$ possible source
2 particle correlations at $|\Delta \eta|<0.7$

- Shoulder structures almost disappeared at 0-20%
- Shoulder is described by $v_3$ and $v_4\{\Phi_4\}$ at small $|\Delta \eta|$
2 particle correlations at $2<|\Delta \eta|<5$

$$C(\Delta \phi) = b^{2P} (1 + 2v_{1,1}^{2P} \cos \Delta \phi + 2 \sum_{n=2}^{6} v_n^{EP} v_n^{EP} \cos n\Delta \phi)$$

- Ridge and Shoulder are described by higher $v_n$ at large $|\Delta \eta|$.

Charged particle pair with large rapidity gap e.g. $|\Delta \eta|>2$
## Motivation

- Ridge and Shoulder can be described by $v_n$ in central collisions

<table>
<thead>
<tr>
<th>Central collisions</th>
<th>Ridge</th>
<th>Shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>small $</td>
<td>\Delta \eta</td>
<td>$ (Au+Au 200GeV)</td>
</tr>
<tr>
<td>large $</td>
<td>\Delta \eta</td>
<td>$ (Pb+Pb 2.76TeV)</td>
</tr>
</tbody>
</table>

- Whether Ridge and Shoulder can be described by $v_n$ at peripheral collisions?
  - How is the correlation changed depending on $|\Delta \eta|$ gap
    - Shoulder structure in small $|\Delta \eta|$ gap is tested with $v_2$, $v_3$ and $v_4$ subtractions

<table>
<thead>
<tr>
<th>Peripheral collisions</th>
<th>Ridge</th>
<th>Shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>small $</td>
<td>\Delta \eta</td>
<td>$</td>
</tr>
<tr>
<td>large $</td>
<td>\Delta \eta</td>
<td>$</td>
</tr>
</tbody>
</table>
Data set & measured value

- **Au+Au 200GeV, 3.2 billion Minimum Bias Events taken in 2007**
  - 2 particle charged hadron correlations at $|\Delta \eta|<0.7$, Centrality : 0-50%
  - Trigger $p_T = 2$~4 GeV, Associate $p_T = 1$~2 GeV
  - $v_n\{\Phi_n\}$ of central tracks ($|\eta|<0.35$) was measured with Event Plane method ($|\eta|:1.0$–2.8)

Simulated Flow with measured $v_n$ and $\Phi_i$-$\Phi_j$ correlations

$C_2(\Delta \phi) \equiv \frac{dN_{pair}^{same}}{d\Delta \phi} \frac{N_{pair}^{mixed}}{dN_{pair}^{mixed}/d\Delta \phi} \frac{N_{pair}^{same}}{N_{pair}^{same}}$

Pair yield per a trigger

$1/N_{trig} dN_{pair}/d\Delta \phi$

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v2, v3 and v4\(\{\Phi_4\}\) subtracted correlations at \(|\Delta \eta|<0.7\)

- Shoulder almost disappeared at centrality 0-10% as previous results
- "New" shoulders emerged in peripheral collisions
  - systematic error is relatively large

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Fitting to **flow subtracted** correlations

\[ \text{Au+Au} \sqrt{s_{NN}} = 200\text{GeV}, h^{+}\text{-}h^{-} \text{ correlations at } |\Delta \eta|<0.7, p_{T}: 2-4 \otimes 1-2\text{GeV} \]

**Fit function:** \( J(\Delta \phi) = \sum_{n=0}^{g} J_{n} \cos(n^* \Delta \phi) \)

- \( \cos(3(\Delta \phi)) \) and \( \cos(4(\Delta \phi)) \) terms are balanced at \( \Delta \phi = \pi \) in central collisions
- \( \cos(4(\Delta \phi)) \) term is almost 0 in peripheral collisions
  - \( \cos(3(\Delta \phi)) \) and \( \cos(4(\Delta \phi)) \) terms aren’t balanced, dip at \( \Delta \phi = \pi \) is emphasized

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**Centrality 0-10%**
- \( : J(\Delta \phi)[\text{total}] \)
- \( : J_{0}(\text{offset}) \)
- \( : J_{1} \cos 1 \Delta \phi \)
- \( : J_{2} \cos 2 \Delta \phi \)
- \( : J_{3} \cos 3 \Delta \phi \)
- \( : J_{4} \cos 4 \Delta \phi \)

- Bands indicates systematic width

**Legend:**
- \( v_{2}, v_{3}, v_{4}\{\Phi_{4}\} \) subtracted with \( <\cos(4(\Phi_{4} - \Phi_{2})> = v_{4}\{\Phi_{2}\}/v_{4}\{\Phi_{4}\} \)
- PHENIX Preliminary

\( \Delta \phi = \phi_{asso} - \phi_{trig} \text{[rad]} \)
Fitting to **flow subtracted** correlations

\[ \text{Fit function: } J(\Delta \phi) = \sum_{n=0}^{8} J_n \cos(n^*\Delta \phi) \]

- \( v_2, v_3, v_4\{\Phi_4\} \) subtracted with \( \langle \cos(4(\Phi_4 - \Phi_2)\rangle = v_4\{\Phi_2\}/v_4\{\Phi_4\} \)
- \( \square: \text{PHENIX Preliminary} \)

![Graph showing correlation](image)

- \( \Delta \phi = \phi_{asso} - \phi_{trig} \) [rad]
- \( \cos^3(\Delta \phi) \) and \( \cos^4(\Delta \phi) \) terms are balanced at \( \Delta \phi = \pi \) in central collisions
- \( \cos^4(\Delta \phi) \) term is almost 0 in peripheral collisions
  - \( \cos^3(\Delta \phi) \) and \( \cos^4(\Delta \phi) \) terms aren’t balanced, dip at \( \Delta \phi = \pi \) is emphasized
Φ₂ & Φ₃ dependent analyses are in progress

Au+Au $\sqrt{s_{NN}} = 200$ GeV, $h^+ - h^-$ C₂ & Flow with respect to Φ₃ at $|\eta| < 0.7$, $p_T < 2-4$ GeV, Cent.20-30%

no $\Phi_n$ alignment mixing
Φ₂ alignment mixing
Φ₃ alignment mixing

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Trigger $\eta$ selected $\Delta \eta$ correlation could be the probe to survey the geometry and/or dynamics of QGP bulk in pseudo rapidity directions with same analogy of Reaction Plane dependent $\Delta \phi$ correlations.
plus/minus triggered correlations have same shape with none triggered correlations

jet-bulk interaction was not observed

experimental sensitivity might be not enough due to limited pseudo rapidity coverage
plus/minus triggered correlations have same shape with none triggered correlations

jet-bulk interaction was not observed

experimental sensitivity might be not enough due to limited pseudo rapidity coverage
Summary & Outlook

- v2 v3 and v4{Φ₄} subtracted Δφ correlations are measured within |Δη|<0.7 in Au+Au 200GeV collisions
  - Shoulder almost disappeared in central collisions as previous results
  - “New” shoulder emerged in peripheral collisions
    - this was due to the imbalance of cos3Δφ and cos4Δφ components
- ηₜₐ₉ dependent Δη correlations
  - Jet correlation might be independent of ηₜₐ₉
  - experimental sensitivity might be not enough
- Outlook for Δφ correlations
  - reduce systematic error width
  - include v₅ and v₆ contributions
  - Φ₂ & Φ₃ dependent analyses are in progress!!
Backup Slides
**Φ_n resolution and Φ_i - Φ_j correlations**

*arXiv:1105.3928v1 [nucl-ex]*

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**FIG. 1:** (color online) Raw correlation strengths (see text) of the event planes for various detector combinations as a function of collision centrality. The detectors in which the event plane is measured are: (a) RXN North, (b) BBC South, (c) MPC North, and (d) MPC South.
Higher harmonic flow

arXiv:1105.3928v1 [nucl-ex]

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PRL 105, 062301(2010)
\( v_2, v_3 \) and \( v_4 \{ \Phi_4 \} \) with model comparison

QM2011 Flow Plenary S. Esumi

\[ \langle V_2 \rangle, \langle V_3 \rangle, \langle V_4 \rangle \]

\[ V_n \]

FIG. 3: (color online) Comparison of \( v_n \{ \Psi_n \} \) vs. \( N_{\text{part}} \) measurements and theoretical predictions (see text): “MC-KLN + 4\( \pi \frac{n}{s} = 2 \)” and “Glauber + 4\( \pi \frac{n}{s} = 1 \) (1)” [16]; “Glauber + 4\( \pi \frac{n}{s} = 1 \) (2)” [17]; “UrQMD” [26]. The dashed lines (black) around the data points indicate the size of the systematic uncertainty.

Compare with the Event Plane method

Consistent between the 2PC and full FCal EP method (Similar for FCal_{P(N)}).

Jiangyong, Jia
QM11' Flow Plenary

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Fourier analysis of the per trigger yield jet function

\[ JF(\Delta \phi) = \sum (C_n \cos(n\Delta \phi)) \]

\[ \text{PHENIX preliminary} \]

\( \text{cos}^3 \Delta \phi \) term from Jet+bulk+Jet-bulk interplay?

\( \text{cos}^3 \Delta \phi \) term from Jet

Moriond QCD 2011
John-Chin-Hao-Chen

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